Section II (Remarks)

April 13, 2007 Interview with Examiner Thao Le

Appreciation is expressed to Examiner Thao Le for the courtesy extended to the undersigned attorney, Steven J. Hultquist, and co-inventor Bruce Baretz, in granting the personal interview conducted on April 13, 2007.

The substance of the April 13, 2007 interview is addressed in Examiner Le's Interview Summary issued at the conclusion of the interview. The interview is further documented by the ensuing remarks, and by the enclosed Declaration under 37 CFR 1.132 by Bruce Baretz, attesting to facts concerning the state of the art at the time the invention was made, and the disclosure and construction of Stevenson et al. US Patent 3,819,974, as discussed during the April 13, 2007 interview.

Acknowledgment of Withdrawal of Claims Pursuant to Restriction Requirement

The examiner's withdrawal of claims 53-69 from further consideration (January 29, 2007 Office Action, page 2, paragraph 2) is acknowledged.

Request for Formal Allowance of Claims 44-52, As Free of Rejection

It is noted that pending claims 44-52[2] have not been rejected on any grounds in the January 29, 2007 Office Action.

It is requested that such claims 44-52 be formally allowed.

Rejections of Claims 31-38, and Traversal Thereof

In the January 29, 2007 Office Action, Examiner Le rejected claims 31-38 on various reference grounds, including:

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[2] introduced in applicants' Response filed November 20, 2006

- a rejection of claims 31-36 under 35 USC 103 (a) as unpatentable over Stevenson et al. US Patent 3,819,974 ("Stevenson") in view of Kitagawa et al. US Patent 5,237,182 ("Kitagawa") or Tadamoto et al. US Patent 5,770,887 ("Tadamoto"); and

- a rejection of claims 37-38 under 35 USC 103 (a) as unpatentable over Stevenson and Kitagawa or Tadamoto as applied to claim 31, and further in view of Ditzik US Patent 5,771,039 ("Ditzik").

Such rejections are traversed.

Reconsideration of the patentability of claims 31-38 is requested, in light of the ensuing remarks.

Patentable Distinction of Claims 31-38 Over the Cited References

As explained by Examiner Le at the April 13, 2007 interview, he cited Kitagawa solely for teaching of an LED emitting radiation in the blue to ultraviolet spectrum, to modify Stevenson by replacing Stevenson's violet light emitting LED with the blue/UV LED of Kitagawa.

Examiner Le stated during the interview that the violet light LED and phosphor combination of Stevenson "inherently produces white light." He identified the disclosure at column 3, line 24 to column 4, lines 7 of Stevenson as the basis for such position.

Applicants vigorously dispute such interpretation of Stevenson. The passage cited by the examiner is set out below:

> "Thus, it is seen that there has been provided an improved light emitting diode capable of emitting light in the violet region of the spectrum. This device may be used as a source of **violet light** for applications where **this spectral range** is appropriate. This light may be converted to lower frequencies (lower energy) with good conversion efficiency using organic and inorganic phosphors. Such a conversion is appropriate not only to develop **different colors for aesthetic purposes**, but also to produce light in a **spectral range of greater sensitivity for the human** eye. By use of different phosphors, all the **primary colors** may

> be developed from this same basic device. An **array of such devices** may be used for **color display** systems; for example, a **solid state TV screen.**"
>
> (emphasis added; Stevenson, column 3, line 24 to column 4, line 7)

The bold text portions of this text clearly show that Stevenson was concerned only with single color output. The term "spectral range" is first used to refer to violet color light, and therefore is properly understood in context as referring to a single color. Stevenson then discusses developing "different colors for aesthetic purposes," which in context refers to distinct single colors. The further reference to a "spectral range of greater sensitivity for the human eye" identifies a single color (since the first use of "spectral range" two sentences earlier refers to the single color violet) to which the eye is more sensitive.

Stevensons' next reference in this text to "primary colors" identifies the single colors of red, green and blue. This is immediately followed by mention of "an array" of such primary color devices as useful for "color display systems" for a "solid state TV screen," thereby specifying a red (R) light device being used with a green (G) light device and with a blue (B) light device to form an RGB array for such solid state TV display application.

The disclosure of Stevenson relied on by Examiner Le therefore teaches away from a "display including at least one light emission device" with LED and luminophoric medium arranged "so that radiation is emitted from the light emission device as a white light output," as required by applicants' broad claim 31, from which each of the remaining rejected claims 32-38 is dependent.

Such construction of Stevenson is supported by the enclosed (in Appendix A) Declaration of co-inventor Bruce Baretz submitted under the provisions of 37 CFR 1.132, attesting to facts concerning the meaning of such disclosure in Stevenson, in the context of the state of the art. Dr. Baretz' Declaration establishes, *inter alia*, that the disclosure in Stevenson:

- "describes the production of light of specific discrete colors, including the production of violet light, and the production of primary colors; that primary colors are red, green and blue; that there is no disclosure in U.S. Patent 3,819,974 (Stevenson et al.) of generating polychromatic white light; and that there is no disclosure in U.S. Patent 3,819,974

(Stevenson et al.) of any phosphor materials that would produce polychromatic white light in response to violet light emitted by the disclosed light emitting diode". (paragraph 9 of the Baretz Declaration);

- "referring to conversion of violet light using phosphors 'not only to develop different colors for aesthetic purposes, but also to produce light in a spectral range of greater sensitivity for the human eye' thereby refers to single discrete colors of light and light of a single color, consistent with the state of the art and conventional wisdom that is described in paragraph 5 hereof and applicable to the interpretation of U.S. Patent 3,819,974 (Stevenson et al.) as of the time the Invention was made by Dr. Tischler and me" (paragraph 10 of the Baretz Declaration); and

- "stating that 'all the primary colors may be developed from this same basic device' and thereafter stating that '[A]n array of such devices may be used for color display systems; for example, a solid state TV screen' refers to an array of LED/phosphor devices in which each such device produces one of the primary colors of red, blue and green, consistent with the state of the art and conventional wisdom that is described in paragraph 5 hereof and applicable to the interpretation of U.S. Patent 3,819,974 (Stevenson et al.) as of the time the Invention was made by Dr. Tischler and me" (paragraph 11 of the Baretz Declaration).

The preceding remarks and the accompanying Declaration evidence of Dr. Baretz show that that Stevenson <u>teaches away</u> from the applicants' claimed invention and provides <u>no derivative basis</u> for such invention.

In view of such "teaching away" from generating a white light output by Stevenson, the examiner's hypothetical modification of replacing the violet light LED of Stevenson with the blue-ultraviolet LED of Kitagawa or with the blue-ultraviolet GaN single crystal emitter of Tadamoto does not and cannot yield the applicants' claimed invention.

In this context, it is highly significant that Kitagawa, at column 3, lines 15-20, acknowledges the violet light LED technology described in the Stevenson patent as being <u>inconsistent with Kitagawa's objective of efficient luminescence</u> (it being noted here that co-inventors David A. Stevenson and Herbert P. Maruska of the Stevenson patent were co-authors of the article, "Violet luminescence of Mg-doped GaN," which appeared in Appl. Phys. Lett., Vol. 22, No. 6, 15 March 1973[3], and contains substantial disclosure of the subject matter of the Stevenson patent).

[3] A copy of this journal article is enclosed in Appendix B of this response, and is made of record in a concurrently filed Supplemental Information Disclosure Statement.

Kitagawa contains the following disclosure at column 3, lines 6-20:

> "In addition, a conventional high-temperature growing method such as CVD is difficult to dope Zn of high vapor pressure in GaN with a precise concentration as desired. As a result, light of undesired colors such as green, yellow or red is prone to be included because such light is produced due to crystal defects caused susceptibly depending on the Zn concentration. Hence, spectral control of luminescence is very difficult as a whole.
>
> "On the other hand, a Mg-doped GaN device was reported to have a luminescent peak at about 430 nm wavelength (H.P. Maruska et al., Appl. Phys. Lett. 22 (1973) 303). Hence, it is apparent that the Mg-doped device is suitable for violet luminescence but not for efficient blue luminescence."

The foregoing shows that Kitagawa seeks to avoid any "undesired colors such as green, yellow or red" that make "spectral control of luminescence... very difficult."

It also shows that Kitagawa, like Stevenson, teaches away from generating a white light output.

It further shows that Kitagawa was aware of the Stevenson/Maruska work, more than 20 years after it had been reported, and over 19 years after Stevenson US Patent 3,819,974 had been issued. Despite such knowledge, Kitagawa contains no disclosure or suggestion of combining a blue-UV light LED with any phosphor.

The question therefore presents itself - if, as contended by the examiner, it is obvious to combine the teachings of Kitagawa and Stevenson, why didn't Kitagawa, who was aware of Stevenson/Maruska's work two decades earlier, attempt any such synthesis? On the contrary, Kitagawa teaches to avoid any color mixing (specifically, to avoid "undesired colors such as green, yellow or red"), and Kitagawa teaches that such mixing makes "spectral control of luminescence... very difficult."

This teaching away in Kitagawa is relevant to the patentability of the applicants' claimed invention, since the fact that the prior art leads away from a particular combination or modification is strong evidence of non-obviousness. See Monarch Knitting Machinery v. Sulzer

Morat GmbH, 139 F.3d 877, 882 (Fed. Cir. 1998); In re Geisler, 36 116 F.3d 1465, 1471 (Fed. Cir. 1997); Kloster Steedsteel AB v. Crucible Inc., 793 F.2d 1565, 1573 (Fed. Cir. 1986).

In this connection, it is fundamental law that in considering a reference for its effect on patentability, the reference is required to be considered in its entirety, including portions that teach away from the invention under consideration. Simply stated, the prior art must be considered as a whole. See W.L. Gore & Associates, Inc. v. Garlock, Inc., 721 F.2d 1540, 1550 (Fed. Cir. 1983), cert. denied, 469 U.S. 851 (1984). "It is impermissible within the framework of section 103 to pick and choose from any one reference only so much of it as will support a given position, to the exclusion of other parts necessary to the full appreciation of what such reference fairly suggests to one of ordinary skill in the art." See also Application of Wesslau, 353 F.2d 238, 241 (C.C.P.A. 1965); Bausch & Lomb, Inc. v. Barnes-Hind/Hydrocurve, 796 F.2d 443, 448 (Fed. Cir. 1986), cert. denied, 484 U.S. 823 (1987).

The teaching away from the examiner's proposed combination by both Stevenson and Kitagawa clearly shows the unobviousness of the applicants' claimed invention.

Similar considerations are applicable to the alternative secondary reference of Tadamoto. Tadamoto refers at column 1, lines 22-27 to a demand for multicolor light emitting displays, and a semiconductor light emitting element that is capable of "emitting light of shorter wavelengths ranging from a blue light wavelength to an ultraviolet wavelength." Tadamoto's disclosure is limited to a blue/UV emitter suitable as a blue device component in a red device/green device/blue device (i.e., RGB) array for multicolor light emitting displays. Tadamoto accordingly adds nothing to the disclosure of Kitagawa, and likewise teaches away from the examiner's proposed combination.

In sum, the cited references of Stevenson, Kitagawa and Tadamoto fail to provide any derivative basis for applicants' claimed invention, as broadly recited in independent claim 31, reproduced below:

> 31. A display including at least one light emission device, wherein each light emission device comprises an LED energizable to emit radiation with an emission maximum in a spectral range of the blue to ultraviolet spectrum, and a

> luminophoric medium arranged to be impinged by radiation emitted from the LED and to responsively emit radiation in a range of wavelengths, so that radiation is emitted from the light emission device as a white light output.

Claim 31 therefore is fully patently distinguished over such references, and otherwise in form and condition for allowance.

Since rejected claims 32-36 depend either directly or indirectly from claim 31, such dependent claims are likewise patentably distinguished over the combination of Stevenson and Kitagawa or Tadamoto.

Concerning the further rejection of claims 37 and 38, over Stevenson and Kitagawa or Tadamoto, as applied to claim 31, and further in view of Ditzik, it has been shown above that the combination of Stevenson and Kitagawa or Tadamoto fails to provide any derivative basis for the applicants' claimed invention as broadly recited in claim 31, since the combination does not and cannot yield a display in which "radiation is emitted from the light emission device as a white light output," as required by claim 31.

Claims 37 and 38 are directed to LCD display and backlight display aspects of the invention. Claim 37 recites "[T]he display of claim 31, comprising a liquid crystal display." Claim 38 recites "[T]he display of claim 31, comprising a backlight display.

Ditzik has been cited for disclosing "a display device comprising a liquid crystal display or a backlight display including LED, col. 3 lines 4" (page 5, January 29, 2007 Office Action), the examiner contending that "it would have been obvious to one of ordinary skill in the art to use the teaching of Ditzik with Stevenson, because LED can be used as a light source for LCD or backlight" (sentence bridging pages 5 and 6 of the January 29, 2007 Office Action).

Considering first the specific passage at column 3, line 4 of Ditzik cited by Examiner Le, it is instructive to consider the entire paragraph of Ditzik in which the cited line 4 appears, in order to develop a contextual basis for the disclosure being relied on by the examiner.

The paragraph of Ditzik at column 2, line 66 to column 3, line 13 is reproduced below, in which the line 4 text relied on by Examiner Le in his rejection is set out in bold italics for ease of reference:

> "Certain flat panel display devices, such as Liquid Crystal Displays (LCD), may require a backlight for better viewability. A number a [sic] backlight technologies are known to provide a relatively uniform light to the back of display panels. Prior art in backlights include electro luminescent, ***fluorescent, incandescent, and LED light sources. A number*** of light guide devices have been used to apply light to the rear of the display panel, using various fiber, glass, and plastic optical guides. However, several problems arise when the display must be viewed under sunlight, twilight, or night conditions. Each of these viewing conditions require different backlighting designs. The new multiple backlight invention described herein solves these problems by providing a simple way of using multiple light sources and integrating their light to the rear of an LCD panel."
>
> (Ditzik, column 2, line 66 – column 3, line 13; emphasis added)

This passage in its entirety simply mentions LED light sources as one of a variety of types of light sources (including electroluminescent, fluorescent, and incandescent) used in the prior art. There is no elaboration of the structure, composition, operating characteristics or any other information or detail relating to what "LED light sources" is or embodies. Further, this passage after mentioning each of these types notes their deficiency in not accommodating varied light conditions ("several problems arise when the display must be viewed under sunlight, twilight, or night conditions").

The solution of Ditzik to this problem is a switchable system in which the user can select one or more of multiple light sources to adjust to a specific ambient lighting condition. Ditzik therefore requires provision of a multiplicity of types of light sources in order to provide the desired flexibility for viewing the LCD under varied ambient light conditions.

The question then becomes, given that Stevenson discloses "[A]n array" of single color light devices "for color display systems," as primary color (red, green, blue) devices, without any disclosure of the need for backlighting of such display, how and why would one, *a priori*, attempt any synthesis of Stevenson or Stevenson/Kitagawa with the LCD teachings of Ditzik?

The references themselves do not provide any clue as to how the single light color devices of Stevenson could be applied or implemented in a backlighting system of Ditzik. There is simply no specificity or guidance in any of the Stevenson, Kitagawa, Tadamoto or Ditzik references to provide any basis or logic for combination. There is no apparent way in which the Stevenson, Kitagawa, Tadamoto and Ditzik references can be combined to yield a display in which "radiation is emitted from the [LED/phosphor] light emission device as a white light output," as required by applicants' broad claim 31.

In fact, the examiner's only declared basis for obviousness of combining Steven/Kitagawa/Tadamoto with Ditzik is his assertion, "because LED can be used as a light source for LCD or backlight" (page 6, lines 1-2 of the January 29, 2007 Office Action). This alleged basis for modification – the "can be used" standard – is <u>legally improper</u> and has been expressly discredited in numerous controlling decisions. See In re Rouffet, 149 F.3d 1350, 1357 (Fed. Cir. 1998); In re Mills, 916 F.2d 680, 682 (Fed. Cir. 1990) ("The fact that references can be modified or combined is insufficient to meet this criterion [of obviousness]").

Further, there is an additional factor relevant to patentability of claims 37 and 38, namely, that in application to LCDs and to backlighting applications, there was no assurance at the time of making the invention that white light LEDs, even if they could be made, would possess sufficient brightness and whiteness to be useful in backlighting and LCD applications.

In view of all of the foregoing, the Examiner's proposed combination of Stevenson and Kitagawa or Tadamoto with Ditzik is at odds with the express disclosures of these references, which contain <u>no logical basis</u> for their combination and in fact <u>teach away</u> from such combination.

Accordingly, claims 37 and 38 are patentably distinguished, for the same reasons as advanced hereinabove in support of the patentability of claim 31, from which they depend.

It is correspondingly requested that the rejection of claims 37 and 38 be withdrawn.

January 29, 2007 Office Action – Examiner's Response to Applicants' Prior Arguments

Concerning prior arguments, the examiner at page 6 of the January 29, 2007 Office Action cites Stevenson as disclosing that light may be converted to lower frequencies with phosphor material, column 3, lines 29-31, and contends that "such conversion is confirmed by the Applicant in page 6 [sic] last paragraph clearly discloses the UV light is absorbed by the phosphor layer, which in turn can offer white light."

This reasoning attempts to infuse the disclosure of Stevenson, relating to generation of single color light (red, green, blue), with an alleged "confirmation" from applicants' disclosure. This is an additional effort by the examiner to construe Stevenson as disclosing generation of white light, but Stevenson nowhere mentions white light, and in fact Stevenson teaches away from white light generation by its teaching to generate single color light output.

The examiner by "importing" applicants' disclosure into the basis of rejection is citing applicants' own specification as a rationale for the rejection of the applicants' claims.

The law is clear that this is impermissible, and that the basis on which patentability is judged cannot come from the invention itself. "[C]are must be taken to avoid hindsight reconstruction" - it is improper to use the applicants' own specification "as a guide through the maze of prior art references." Grain Processing Corp. v. American Maize-Products Corp., 840 F.2d 902, 907 (Fed. Cir. 1988); Orthopedic Equip. Co. v. U.S., 702 F.2d 1005, 1012 (Fed. Cir. 1983); In re Zurko, 111 F.3d 887 (Fed. Cir. 1997).

The applicants' claims 31-38 are patentable over the art.

The recent U.S. Supreme Court decision in KSR International Co. v. Teleflex Inc., 550 U.S. ___ (2007) does not change this result. Although that case held that the teaching, motivation or suggestion test should not be strictly applied in determining obviousness, it remains true that there must be a reason in logic and fact for combining references, and that references that teach away from the invention are evidence of the non-obviousness of a claimed invention.

Under pre-KSR or post-KSR standards - the above combinations of Stevenson, Kitagawa, Tadamoto, and Ditzik fail to render the applicants' claims obvious. The Supreme Court in KSR reaffirmed the Graham factors, according to which the applicants' claims are not obvious, and merit allowance.

It is fundamental to a proper 103 rejection of claims that an examiner must present a convincing line of reasoning supporting the rejection. See MPEP 2144 ("Sources of Rationale Supporting a Rejection Under 35 U.S.C. 103"), citing *Ex parte Clapp*, 227 USPQ 972 (Bd. Pat. App. & Inter. 1985). The U.S. Supreme Court in KSR affirmed the validity of such approach, stating that "there must be some articulated reasoning with some rational underpinning to support the legal conclusion of obviousness." The Court also reaffirmed the principle that a factfinder judging patentability "should be aware, of course, of the distortion caused by hindsight bias and must be cautious of arguments reliant upon ex post reasoning."

Here, there is nothing in the hypothetical combination of cited references that yields or provides a derivative basis for the applicants' claimed invention of a display in which "radiation is emitted from the light emission device as a white light output," as required by applicants' claim 31, and all claims dependent thereunder.

Claims 31-38 are therefore patentable, and merit allowance.

Petition under 37 CFR 1.136

Petition hereby is made under the provisions of 37 CFR 1.136 for a one-month extension of time for reply to the January 29, 2007 Office Action, extending such deadline to May 29, 2007.

The fee of $120 specified in 37 CFR 1.17(a)(1) for such one-month extension is enclosed by a Credit Card Payment Form authorizing charging of such amount to the credit card specified in the Form. Authorization also is hereby given to charge the amount of any deficiency probably payable for this response, to Deposit Account No. 08-3284 of Intellectual Property/Technology Law.

CONCLUSION

For all the foregoing reasons, it is requested that the rejections of claims 31-38 be withdrawn, and that claims 44-52, which have not been rejected on any grounds, be formally allowed.

The examiner again is thanked for the courtesy of the interview held in his office on April 13, 2007, and the opportunity afforded to the applicants to introduce evidence into the record showing the clear basis of patentability of claims 31-38.

The record of this application confirms the patentable character of claims 31-38 over the art, and warrants the issue of a Notice of Allowance for claims 31-38 and 44-52. Such action is respectfully requested.

If any issues require further resolution, the examiner is requested to contact the undersigned attorney at (919) 419-9350 to discuss same, so that the prosecution of this application can be concluded in favor of issuance of a U.S. Patent for this application.

Respectfully submitted,

Steven J. Hultquist
Reg. No. 28,021
Attorney for Applicants

**INTELLECTUAL PROPERTY/
TECHNOLOGY LAW**
Phone: (919) 419-9350
Fax: (919) 419-9354
Attorney File No.: 4241-198-CON-RCE

<u>Enclosures</u>:
Appendix A: Declaration of Bruce Baretz under 37 CFR 1.132
Appendix B: copy of Marushka et al. Appl. Phys. Lett. Article

The USPTO is hereby authorized to charge any deficiency or credit any overpayment of fees properly payable for this document to Deposit Account No. 08-3284

APPENDIX A

12. THAT the disclosure of U.S. Patent 3,819,974 (Stevenson et al.) quoted in paragraph 8 hereof does not contain any information that embodies or provides any derivative basis for the Invention.

As a below-named declarant, I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements are made with the knowledge that willful false statements, and the like so made, are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the present application or any patent issued thereon.

Bruce H. Baretz
BRUCE H. BARETZ

29 MAY 2007
DATE

APPENDIX B

Violet luminescence of Mg-doped GaN †

H.P. Maruska and D.A. Stevenson
Department of Materials Science and Engineering, Stanford University, Stanford, California 94305

J.I. Pankove
RCA Laboratories, Princeton, New Jersey 08540

(Received 1 November 1972)

The photoluminescent and electroluminescent properties of GaN-GaN:Mg diodes are described. Visible violet electroluminescence was observed with excitation voltages of 10–20 V with the emission peak in the region of 2.9 eV. The I-V characteristics showed $I \propto V^4$ in the region where light was emitted, and the observed power efficiency was approximately 10^{-5}. A photoluminescence peak at 2.9 eV provided additional evidence for an acceptor level, associated with the Mg impurity, about 0.5 eV above the valence band.

Gallium nitride (GaN) is a III-V compound semiconductor which has recently attracted interest for its photoluminescent and electroluminescent properties.[1-9] Light emitting diodes (LED's) have been fabricated from GaN which emit at various wavelengths throughout the visible spectrum and in the near ultraviolet,[6-9] as discussed in a recent review paper.[10] Undoped GaN always occurs highly n type ($n > 10^{18}$ cm^{-3}) and thus far has not been made conducting p type. However, deep acceptors may be used to compensate the donors and produce insulating (i) crystals. Zinc, which is a common acceptor in III-V compounds, has been used to produce i-n junctions in GaN, and LED's have been produced with zinc which emit red, yellow, green, and blue light.[9] The compensation of GaN by the incorporation of Mg has recently been reported, and violet light was obtained using point contacts on the samples; however, excessively high voltages (~160 V) were necessary to excite the luminescence.[7] The present letter reports new developments in the fabrication of violet junction LED's using GaN:Mg requiring 10–20 V for operation.

Single-crystal epitaxial GaN layers were grown by the open-flow vapor-growth process previously described.[7,11] Gallium is transported as its gaseous monochloride, and the nitrogen is introduced into the growth zone in the form of ammonia. The Mg for doping is supplied as its elemental vapor from a side furnace. Single-crystal oriented flame-fusion-grown sapphire slices were used as substrates. After the growth of an undoped n-type region, Mg was introduced to grow the i-type layer. The wafers were cut into 1-mm squares. Contact to the two regions was made with an indium amalgam using a technique developed for GaAs.[12] This amalgam is a liquid at room temperature and was painted onto one edge to form an Ohmic contact to the n region and onto the face of the insulating region. The chip was then heated for 1 min at 400 °C to drive off the mercury, leaving solid indium contacts. The devices were then either glued to glass slides with glycol-phthalate (sapphire to glass) or mounted on TO-15 transistor headers (sapphire up, see Fig. 1.).

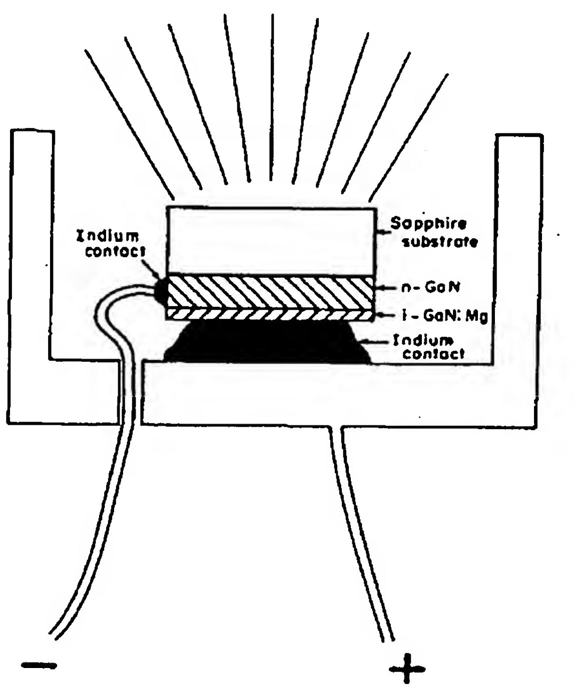

FIG. 1. Schematic diagram of the GaN:Mg electroluminescent diode.

Electroluminescence was obtained both with "forward"

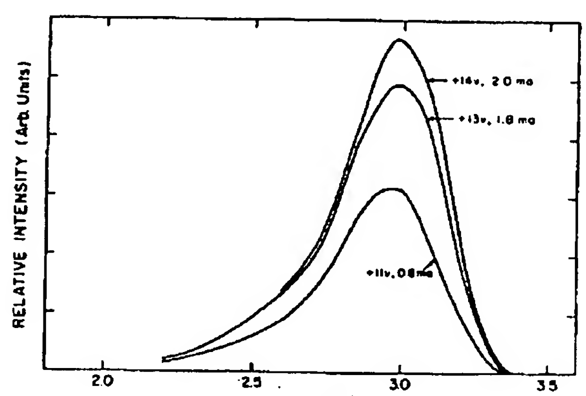

FIG. 2. Electroluminescent spectrum with forward bias.

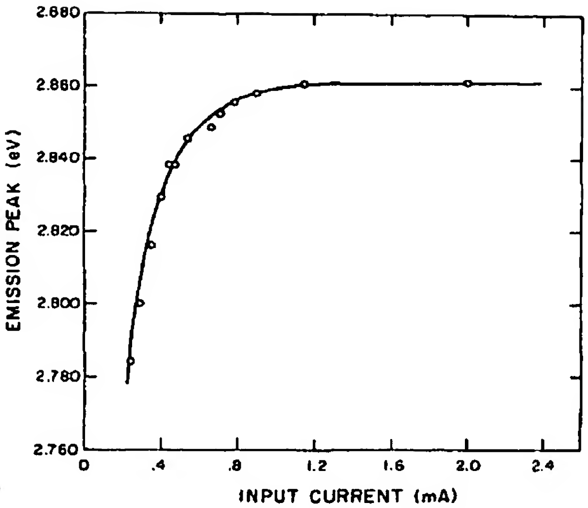

FIG. 3. Shift of forward-bias electroluminescence peak with input current.

(*i* layer biased positive) and "reverse" bias, although the forward-bias luminescence was more efficient. In the forward direction, substantial conduction began at about 10 V, and violet light, readily seen in a well-lit room, was obtained at 20 V. Under reverse bias, conduction occurred in the 40- to 60-V range and produced green light. Emission under forward-bias electroluminescence peaked in the region 2.86—2.98 eV in various samples. The spectral width at half-maximum is about 400 meV. A typical spectrum is shown in Fig. 2. The peak has been found to shift to shorter wavelengths with increasing current until a saturation value is reached. An example of this effect is shown in Fig. 3. The light output increases superlinearly with current but linearly with power input. In reverse bias, a broad peak centered at 2.5 eV and about 750 meV wide at half-maximum is obtained. This is shown in Fig. 4. We do not yet understand the shift in emission wavelength from forward to reverse bias.

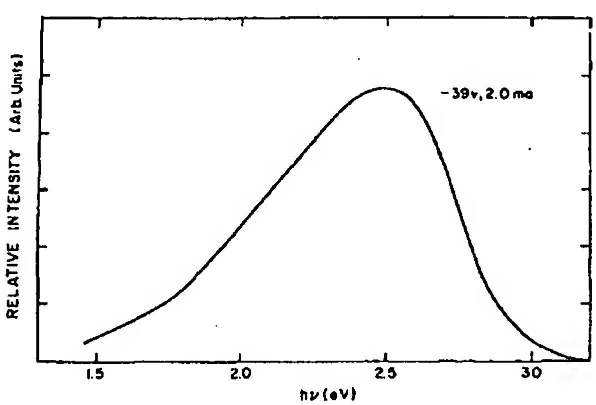

FIG. 4. Electroluminescent spectrum with reverse bias.

The *I-V* characteristic of a typical device is displayed in Fig. 5(a). The current drawn by a particular sample is dependent on the contact area, but since the emitted light shows a very nonuniform pattern, it is not possible to ascertain the current density. A log-log plot of the *I-V* characteristics is shown in Fig. 5(b). With forward bias, $I \propto V^3$ in the region $10 < V < 30$ V where the light is emitted. A steeper dependence is found at smaller voltages. At a given voltage the reverse current is about two orders of magnitude smaller.

The power efficiency increases with increased forward bias up to 15 V, beyond which it is nearly constant at a value of 10^{-5}. The reverse-bias efficiency is an order of magnitude lower (see Fig. 6). The diodes operate continuously at room temperature.

Photoluminescence of Mg-doped GaN was excited with a He-Cd laser which emits at 3250 Å, and the resulting spectrum was found to peak at 2.925 eV at 77 °K (Fig. 7). This indicates that the Mg complex forms a level about 0.5 eV above the valence band in GaN. It has been suggested[5] that Zn first forms a shallow acceptor level when present in small quantities and with increased doping results in a deep Zn-donor complex, which compensates the native donors present and is responsible

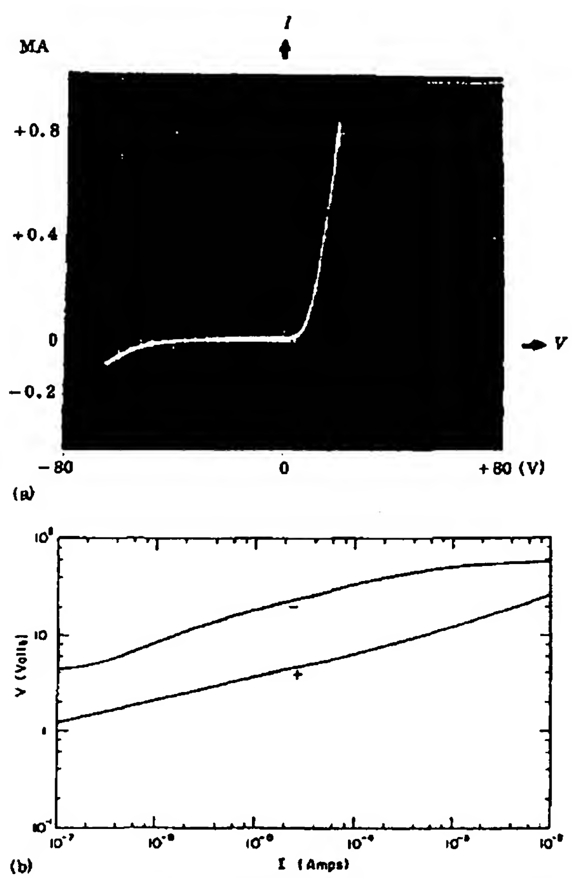

FIG. 5(a) Typical *I-V* characteristic. (b) Log-log plot of *I-V* characteristic.

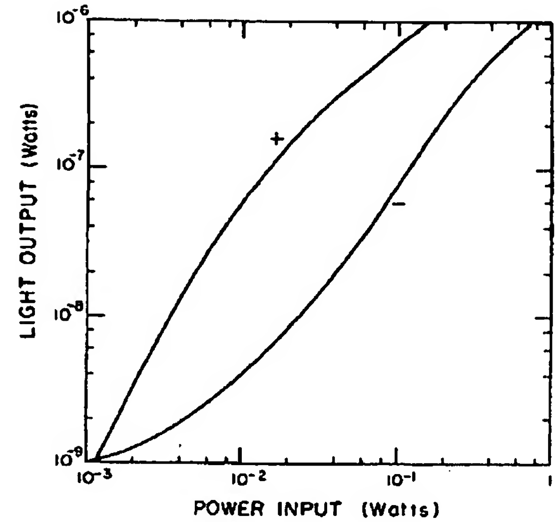

FIG. 6. Power efficiency.

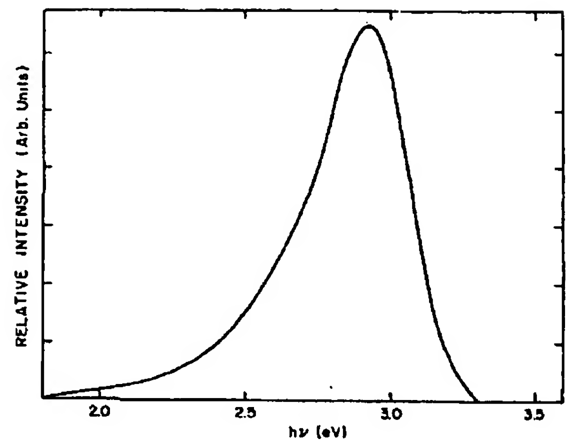

FIG. 7. Photoluminescence spectrum at 77 °K.

then for the resistivity increase and sample color changes which are observed. It is reasonable to assume that the same process holds for Mg doping. Although the photoluminescence results were obtained at 77 °K, one may expect that there will no shift in this spectrum in going to room temperature.[13] Thus, the forward-bias electroluminescence at 300 °K corresponds well to the photoluminescence data, and the same level is apparently involved.

The foregoing results show that it is possible to obtain electroluminescence in Mg-doped GaN diodes which require about 20 V for operation and which can emit at shorter wavelengths than Zn-doped GaN diodes. A power efficiency similar to that found in the Zn-doped blue-emitting diodes is found, and the luminescence is readily seen in a well-lit room, in spite of the eye's decreased sensitivity in the violet region of the spectrum. The $I \propto V^3$ characteristic is suggestive of space-charge-limited current in the presence of an exponential distribution of the traps.[14] An exponential distribution of traps is consistent with the shift of the light emission peak to shorter wavelengths with increased input current. If it is assumed that the traps are being emptied by field emission, then levels nearer the valence band (which will have a greater density) will be emptied at higher applied fields. However, a maximum in the distribution of traps must be assumed to explain the saturation when the traps of maximum density are being emptied (Fig. 3).

This research is being continued in an effort to further elucidate the mechanisms responsible for the light generation, and to learn more about the properties of the magnesium center.

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